Transactions of the Royal Society of S. Aust. (1996), **120**(1), 21-36.

PRELIMINARY INVESTIGATIONS OF DUNES OF THE GAWLER RANGES PROVINCE, SOUTH AUSTRALIA

by E. M. CAMPBELL*, C. R. TWIDALE*, J. T. HUTTON† & J. R. PRESCOTT‡

Summary

CAMPBELL, E. M., TWIDALE, C. R., HUTTON, J. T. & PRESCOTT, J. R. (1996) Preliminary investigations of dunes of the Gawler Ranges province, South Australia. *Trans. R. Soc. S. Aust.* **120**(1), 21-36, 31 May, 1996.

Three fields of dunes have developed in the recent past within the Gawler Ranges in the arid-semiarid interior of South Australia. The dunes (lunettes, parabolic dunes, transverse dunes, linear dunes, climbing dunes and falling dunes) are essentially relic forms, were active about 4000 years BP and are now stabilised by vegetation though strong winds still cause occasional sand movement. Some of the dunes demonstrate sand transport over distances of at least 25 km. The origin of the various morphological dune types is discussed. Supply of sand, the moisture content of the substrate, the vegetation cover and wind speed and direction are all important. Topography influences the morphology of the dunes in various ways and is fundamental to any explanation of climbing and falling dunes.

KEY WORDS: Gawler Ranges, lunettes, parabolic dunes, transverse dunes, linear dunes, climbing dunes, falling dunes, thermoluminescence dating.

Introduction

In the mid-latitude deserts extensive fields of sand dunes are restricted to plains. Sand dunes have, however, been reported from desert uplands where topographic obstacles deflect or funnel the regional airflow and produce depositional forms and patterns different from the essentially regular and repeated formations found in the dunefields of the adjacent plains (Wilson 1973; Smith 1982). They include sand shadows of various types, sand sheets, obstacle dunes and climbing and falling dunes (Planhol & Rognon 1970; McKee 1979; Mainguet 1984; Greeley & Iverson 1985). The Gawler Ranges, located in the arid-semiarid interior of South Australia, is a desert upland within which three fields of sand dunes have penetrated the valleys between the bornhardt massifs and in some areas have overridden the low domical hills (Fig. 1a, b).

Geologic Background

The bornhardts of the Gawler Ranges are developed in a layered sequence of silicic volcanic rocks (mainly rhyolites, rhyodacites and dacites) of Mesoproterozoic age (1592 ± 2 Ma - Fanning *et al.* 1986). The volcanic rocks consist predominantly of subaerially erupted ignimbrites (*nuées ardentes* deposits), welded to varying degrees, and with local occurrences of basaltic lava and agglomerate. They were intruded by granites of the Hiltaba Suite (1485 ± 16 Ma - Creaser 1989 cited by Blissett *et al.* 1989; see also Flint 1993) which now occur extensively in the western part of the upland, in the Kondoolka and Hiltaba areas, as well as in small isolated outcrops near Kokatha Homestead (H.S.) and Lake Everard H.S. They are also exposed to the W, SW and S of the Ranges.

Where exposed, both the volcanic and granitic crystalline rocks are massive and compact but a well developed system of orthogonal fractures trending NNW and NE, and including also latitudinal and

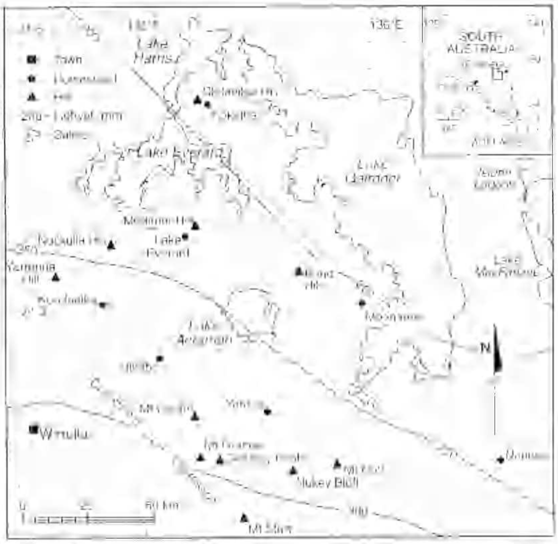

Fig. 1a. The Gawler Ranges province, showing location of the study site in South Australia (inset), localities mentioned in the text and average annual isohyets (mm). The Corrobinnie Depression dune samples analysed by Gostin were collected from dunes adjacent to the road from Wirrulla to Hiltaba H.S.

---

* Department of Geology and Geophysics, University of Adelaide S. Aust. 5005.

† Deceased.

‡ Department of Physics, University of Adelaide S. Aust. 5005.

meridional sets, has been exploited by weathering and erosion to form the major valley systems of the Ranges (Campbell & Twidale 1991). The summit and upper slopes of the bornhardts are essentially devoid of any weathered materials, though isolated patches of regolith are preserved on the lower slopes, as for example 7 km east of Nonning H S., and in the valley floors drill cores and dam sections indicate that the volcanic material is weathered to depths of up to 50 m. Individual bornhardts attain heights of over 460 m in the S, but they decline in elevation to the N (e.g. Nukey Bluff c. 460 m, Mt Nott 430 m, Bond Hill 336 m, Chitanilga Hill 317 m, Nuckulla Hill 256 m, Mortimer Hill 232 m – see Fig. 1a). The upland is bounded on its SW and S sides by an escarpment which, though dissected and rising only 150-200 m above the surrounding plain, is nevertheless, and viewed regionally, linear and imposing, so much so that the explorer E. J. Eyre was led to describe the Gawler Ranges as "a vast mountain mass rising abruptly out of the low scrubby country" (Eyre 1845). To the N, W and E the relief amplitude diminishes and the hills peter out as the plains become more and more extensive.

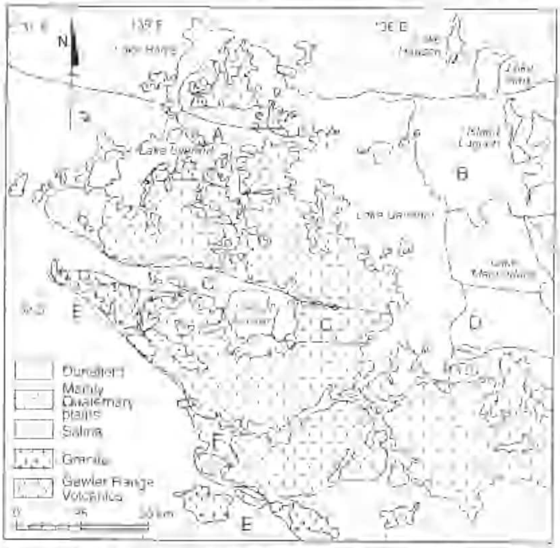

Fig. 1b. The geology, including dunefields, of the Gawler Ranges province (after Williams 1994). A. Hiern Dunefield. B. Piccadilly Dunefield. C. Moonaree Dunefield. D. Beacon Dunefield. E. Ilkina Dunefield. F. Scrubby Peak Dunefield.

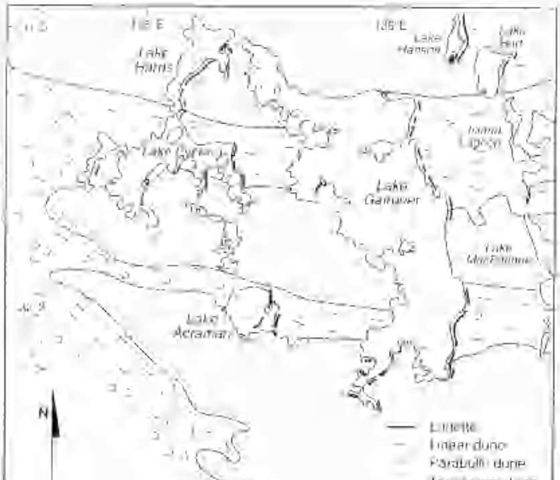

Fig. 1c. Schematic diagram showing location of lunettes, linear dunes and parabolic dunes of the Gawler Ranges province, South Australia. The orientation of the linear dunes is also indicated. Not all dunes are shown.

The bornhardts of the Gawler Range province have evolved in two major stages. The first involved planation and fracture-controlled differential subsurface weathering in Jurassic or earlier times, the second, the stripping of the regolith in the Early Cretaceous to expose bevelled domical forms. Remnants of the etch planation surface represented by the summit bevels are particularly well preserved in the south. There has been only minor erosion of the ranges since the Mesozoic (Campbell 1990[1]; Campbell & Twidale 1991).

Numerous salinas, including lakes Gairdner, Harris, Everard and Acraman and many small saline playas, occupy low lying areas in valleys and plains. The depression occupied by Lake Acraman is the site of an ancient meteorite impact (Williams 1994). The large lakes stand about 120 m above sea level. They are the termini of closed drainage basins most of which are not much larger than the lakes themselves.

Climate

At present the area is semiarid in the S grading to arid in the N (Fig. 1a). In the south there is a pronounced winter rainfall maximum, produced predominantly by the easterly passage of cold fronts, but a significant proportion of the rainfall is derived from occasional influxes of moist tropical air. In the north the rainfall is derived from both these sources and the annual distribution is more uniform (Fig. 2a; Bureau of Meteorology 1993a). Summers are hot and winters cool. Annual evaporation is about 2700 mm, with a mean monthly evaporation ranging from about 80 mm in June to 390 mm in January.

The only records for modern wind regimes in the area are from Nonning (Fig. 2b). In summer, sand-moving winds (stronger than about 20 km per hour) blow predominantly from SE, S and SW. In winter, strong winds blow from several quarters but N, NW

---

[1] CAMPBELL, E. M. (1990) Structure and surface in the Gawler Ranges, South Australia. PhD thesis, University of Adelaide (Unpub.)

and SW winds are important (Bureau of Meteorology 1993b). Woomera, located more than 100 km to the NE of the Ranges, experiences predominantly SE-S (total) winds in summer although in winter, winds are more variable, but with a strong N and NW-SW component. At Ceduna, 100 km to the W, in summer SE, S and SW winds predominate, whilst in winter NE through NW-SW winds are most common (Bureau of Meteorology 1988; Fig. 2c).

The Dunefields

The Australian dunefields form a huge whorl of linear dunes around the centre of the continent (Brookfield 1970; Wasson *et al.* 1988), though it is not established whether all the sectors of the pattern were formed by winds related to one and the same atmospheric system or that they were ever active at the same time. The Australian desert dunes are characteristically long, parallel sand ridges extending unbroken over tens and even a few hundreds of kilometres. Many are asymmetrical in cross-section and display tuning fork or Y junctions. They are generally restricted to the desert plains (Madigan 1936, 1946; Wopfner & Twidale 1967).

Although the precise mechanism of formation is debated, and it is likely that the dunes originate in various ways (McKee & Tibbetts 1964; Wopfner & Twidale 1967; Brookfield 1970; Tsoar 1989; Tseo 1993), some are apparently initiated in the lee of lunettes or other accumulations of sand (Twidale 1972) and extend in a downwind direction. There is a mild controversy as to whether the sand of which the dunes are built is of local derivation (Folk 1971; Wasson 1983) or whether it is essentially exotic and far-travelled (Wopfner & Twidale 1967). The Gawler Ranges dunefields yield evidence germane to this problem.

Immediately to the W of the Gawler Ranges the linear sand ridges of the Great Victoria Desert, the southern part of the great Australian dune pattern, trend WNW to ESE and there are zones of parabolic dunes. Within the Gawler Ranges province the sand dunes are more varied and lunettes, transverse dunes, and climbing and falling dunes, as well as linear and

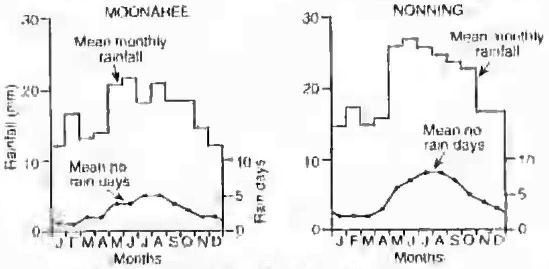

Fig. 2a. Mean monthly rainfall and mean number of rain days for Moonaree and Nonning (Bureau of Meteorology 1993a). Length of record: Moonaree - 108 years, Nonning - 90 years.

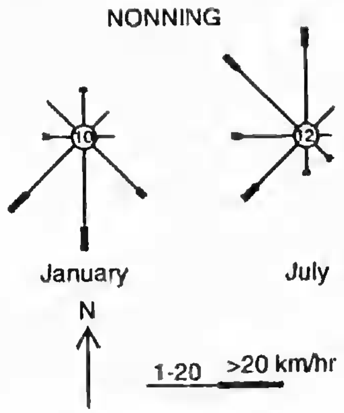

Fig. 2b. Nonning wind data (Bureau of Meteorology 1993b). The percentage of calm observations is indicated in the centre of the rose. Length of record 23 years.

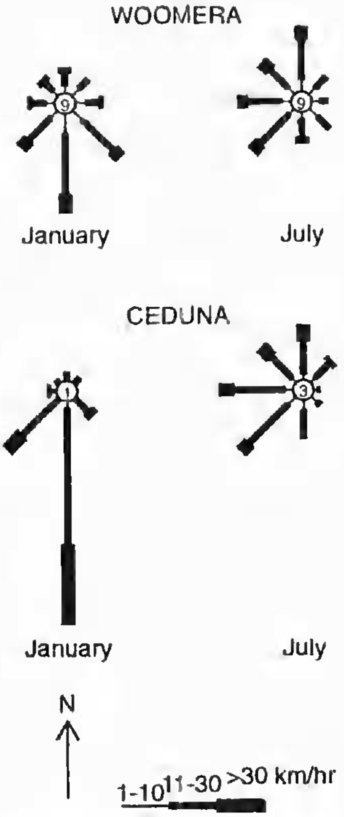

Fig. 2c. Wind roses for Woomera and Ceduna (Bureau of Meteorology 1988). The percentage of calm observations is indicated in the centre of the rose.

parabolic dunes, are developed. Some are stable, but others are occasionally mobile.

Three fields of dunes penetrate the uplands (Fig. 1b). In the N, the Hiern Dunefield extends WNW to ESE between the Kokatha hills and Lake Everard to the western shore of Lake Gairdner. The dunes are predominantly linear forms. Dunes also occur N of the Ranges and also on some of the islands within Lake Gairdner. In the same latitude, and to the lee of a major lunette developed on the E shore of Lake Gairdner, the Piccadilly Dunefield extends eastwards for 35 km across the plains located between Lake Gairdner and Island Lagoon. Here linear sand ridges and parabolic forms are well developed and some lunettes occur on the eastern margin of small salinas.

The Moonaree Dunefield occupies the plain between the volcanic Everard hills to the N and the granitic Kondoolka hills to the S and extends eastwards to Lake Acraman. In this part of the Moonaree Dunefield there is a sharp boundary between parabolic dunes to the S and linear sand ridges to the N. Dunes occur on islands within Lake Acraman and on its eastern shore. To the NE of Lake Acraman the plain carries a veneer of sand but dune forms are absent. Further to the E, however, linear sand ridges are again developed and extend as far as the shore of Lake Gairdner. Immediately to the W of this salina, some of the dunes override the low volcanic hills forming climbing and falling dunes. The Beacon Dunefield (the Black Oak dunefield of Smith 1976[2]) extends eastwards from the E shore of Lake Gairdner, again in the lee of a major lunette. This field consists mainly of linear sand ridges but there are some lunettes and parabolic forms.

The most southerly dunefield, the Ilkina Dunefield, is part of the Kododo Dunefield of Smith (1976[2]). Both the field and individual dunes trend NW to SE between the Corrobinnie Depression (Bourne *et al.* 1974; Binks & Hooper 1984) and the SW margin of the Gawler Ranges from near Yarranna Hill to the vicinity of Mt Sturt. Within the Corrobinnie Depression, complex parabolic forms are well developed. In the vicinity of Mt Centre, linear sand ridges from the Ilkina Dunefield diverge ESE and extend across narrow plains and valleys between the volcanic uplands and extend into the hilly areas to form the Scrubby Peak Dunefield (Fig. 1b). In both the N and S arms of this dunefield there are departures from the general ESE trend as a result of topographic interference with the airflow. Both crestal transverse dunes and climbing and falling dunes result from such topographic effects.

Dune morphology

Linear dunes

Linear sand ridges dominate the dunefields within the Gawler Ranges (Fig. 3). These linear forms trend WNW to ESE in the W and latitudinally further to the

Fig. 3. Linear sand ridges of the Scrubby Peak Dunefield funnelled along broad valleys between the bornhardts of the southern Gawler Ranges, South Australia. Field of view in foreground approximately 5 km.

---

[2] SMITH, D. M. (1976) The denudation chronology of the southern Gawler Ranges and adjacent areas. MA thesis, University of Adelaide (Unpub.)

E. In places, e.g. near Mt Granite (Fig. 4), funnelling of the wind has produced dunes aligned at various angles to the regional trend. The linear dunes vary in height, length and linear frequency, i.e. the number of sand ridges per unit distance measured normal to the dune trend. The maximum height of the dunes varies from 5-15 m above the interdune corridors. They vary in length from a few tens of metres up to 20 km; none extends unbroken for many scores or hundreds of kilometres as do some of the sand ridges of desert plains such as the Simpson Desert (Wopfner & Twidale 1967, 1990; Twidale 1981). The linear frequency of the dunes varies between two and six per km. The interdune corridors are sand covered. Most of the dunes are symmetrical, with smooth crests which rise and fall to form peaks and saddles. The slopes are gentle, considerably less than the angle of repose of the sand. No depositional structures and no slip faces have been noted. The dunes carry a covering of low shrubs and small trees, though little or no soil development is apparent and there is, today, only occasional and minor reworking of the sand by wind and water. The dunes are relic according to the classification of Livingstone & Thomas (1993).

Parabolic dunes

Groups of parabolic or U-dunes occur within the linear dunefields. Most of the parabolic dunes occur outside the Ranges, and notably in the Corrobinnie Depression (Bourne *et al.* 1974), though there is a W-E zone within the Moonaree Dunefield and patches of parabolic forms occur within the Piccadilly and Beacon dunefields. Although many of these dunes are complex in plan form, with transverse, rake-like and circular patterns well developed, the basic unit is a U-shaped dune about 8 m high and with the open end of the U pointing to the W (Fig. 5).

Fig. 4. Schematic diagram of linear dunes oriented NW to SE, and irregular patterns of linear and transverse dunes due to topographic interference to the wind near Mt Granite, Gawler Ranges, South Australia (from aerial photographs, Department of Lands, South Australia and 1:100 000 National topographic map series). Not all dunes are shown.

Climbing and falling dunes

In the Gawler Ranges most of the dunes are developed on broad valley floors between the bornhardts. In some areas, however, linear dunes penetrate into the hilly terrain and suffer modification as a result of funnelling and diversion of the wind (Fig. 4). In other areas, the dunes extend over the bornhardts. On the reasonable assumption that the sand migrated southeastwards, dunes piled against the windward (northwestern) slope of a hill are termed climbing, or rising, dunes; where sand has overridden the crest of a hill and extended on to the leeward (southeastern) slope, falling, or hanging, dunes are formed (Fig. 6a).

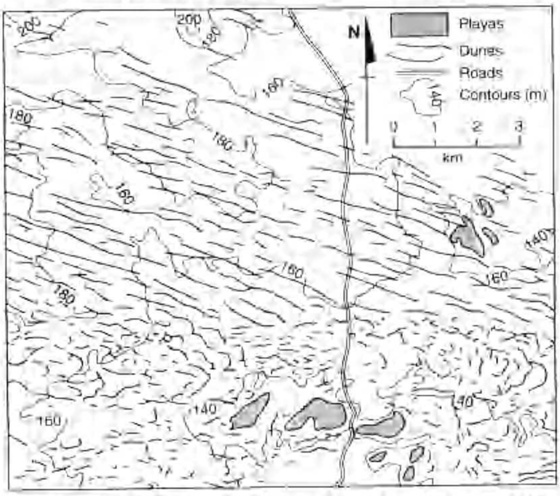

Fig. 5. Linear and parabolic dunes of the Moonaree Dunefield 15 km south of Lake Everard H.S. (from aerial photographs Department of Lands, South Australia and 1:100 000 National topographic map series).

Fig. 6a. Echo, climbing and falling dunes (after Mabbutt 1977). Arrow indicates direction of the wind. A. Linear dune not anchored by topography. B. Linear dune rising over topographic obstacle. C. Climbing (1) and falling (2) dune. D. Echo dune.

These dunes have not been studied in detail in the arid mountains of Australia, although dunes which arguably ascend cliffs have been studied in the coastal context (Jennings 1957; Langford-Smith & Thom 1969).

Climbing and falling dunes are known from various parts of the world, for example from periglacial Finnish Lapland (Seppala 1993), coastal west Galicia, Spain and NE Spain (Cros & Serra 1993), but most previously published reports pertain to warm desert environments, e.g. California (Evans 1962; Smith 1967 cited by Bender 1982; Anders 1974 cited by Bender 1982; Lancaster 1994), Colorado (Johnson 1968), Idaho (Koscielniak 1973[3]), Arizona (Greely & Iverson 1985) and Utah (Alhbrandt 1979), all in the United States, where most are inactive, veneered by gravel and dissected by ephemeral streams (Smith 1982), northern Mexico (Stone 1967), Brazil (Bigarella 1975, 1979), Egypt and Jordan (McKee 1979), the Sinai Peninsula (Ahlbrandt 1979), the Sahara (Smith 1954) and the central Namib Desert (Goudie 1972). They are also found in the eastern Flinders Ranges, South Australia (Green 1994[4]), near Port Stephens and in the Shoalhaven River area in New South Wales (Thom *et al.* 1994), on the Erldunda Range 160 km south of Alice Springs and on the northern margin of the Simpson Desert where dunes override some of the latitudinal ranges. Greeley (1985, Fig. 7.39) illustrates a field of climbing dunes drifting over the rim of a 16 km diameter crater on Mars.

In the Gawler Ranges climbing and falling dunes occur in three areas. First, examples were noted by Smith in the Scrubby Peak Dunefield (1976[2]; Fig. 6b, c). Second, Giles (1980[5]) remarked that sand dunes encroach on to the slopes of Mt Sturt. Sand from the Ilkina Dunefield has accumulated on the NW slopes of Mt Sturt (the western peak) and forms an irregular mound along the base on its SE side. Third, climbing and falling dunes are common in the Moonaree Dunefield E of Lake Acraman, where small dunes trending W-E are essentially restricted to the plains, though they partially override many of the bornhardts (Fig. 6d).

In the Scrubby Peak Dunefield, some linear dunes have been diverted around the major volcanic hills (Figs 4, 6b,c) but elsewhere, especially where the relief is lower, the dunes traverse hill and valley alike. The dunes ascend the lower hills (in general terms those that stand less than some 40 m above the adjacent valley floors) without significant interruption of form and are classed as climbing dunes. In some instances the dune is diverted around the flanks of the hill and continues downwind (Fig. 6b). Elsewhere, the dune form is interrupted, for although there are many grains and even small pockets of sand in fissures and shallow rock basins on the crests and upper slopes of the hills, there is no dune form; a short distance downslope from the crest, however, the dune form is resumed in falling dunes 3-4 m high (Fig. 6c).

Transverse dunes

In the Scrubby Peak Dunefield funnelling of the wind has produced dunes of varied orientation. In this part of the Gawler Ranges elongate bornhardts are aligned essentially N-S. Sand ridges also aligned N-S are located in the valleys between the bornhardts. There are some W-E dunes which override the bornhardts and, in addition, N-S trending elongate dunes are located just below the crest on the lee side of these hills (Figs 4, 7). These crestal dunes are tentatively classified as of transverse type.

Lunettes

Lunettes are developed along at least part of the E side of most of the large salinas and many of the smaller playas in the region (Fig. 1c). Lunettes are transverse dunes located on the lee shores of lake basins. The name "lunette" was first applied to the form by Hills

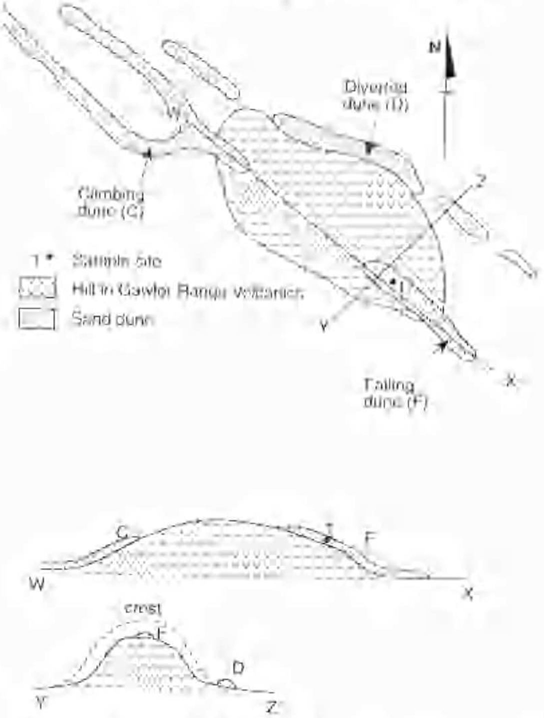

Fig. 6b. Scrubby Peak area, Gawler Ranges, South Australia, showing diverted dune (D), climbing dune (C) and falling dune (F) (from 1:100 000 National topographic map series). The dune-forming winds were from the northwest sector.

---

[3] KOSCIELNIAK, D. E. (1973) Eolian deposits on a volcanic terrain near Saint Anthony, Idaho. MA thesis, University of New York (Unpub.)

[4] GREENE, S. J. (1994) A geomorphological and sedimentological study of a climbing dune, northern Flinders Ranges, South Australia. BA (Hons) thesis, University of Adelaide (Unpub.)

[5] GILES, C. W. (1980) Spring Hill, southern Gawler Ranges. Geol. Soc. Aust. S.A. Div. Geological Monuments III, File E 20 (Unpub.)

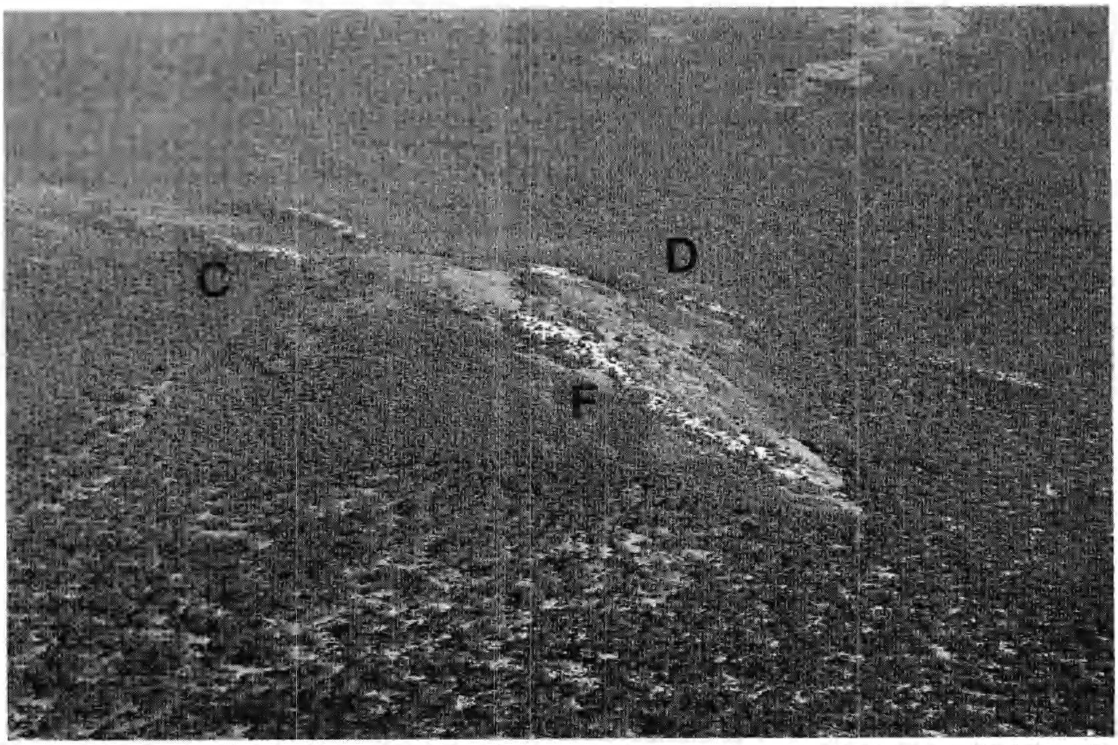

Fig. 6c. Diverted dune (D), climbing dune (C) and falling dune (F), Scrubby Peak area, Gawler Ranges, South Australia. View to the north. The hill stands about 25 m above the surrounding plain.

Fig. 6d. Climbing and falling dunes, Moonaree Dunefield, Gawler Ranges, South Australia. Note that the falling dune, on the near side of the bornhardt, resumes in a topographic embayment. Field of view approximately 2 km.

(1940) who described lunettes of silty-clay compositions from NW Victoria. Subsequently, lunettes of various sizes and mineralogies have been reported from all states of Australia. They range in composition from quartz-rich to clay-rich to almost pure gypsum. The sandy quartz-rich dunes were formed by deflation from beaches on the lake margin. The clay-rich dunes were derived by deflation of clay aggregates from the saline lake floors. The gypsum dunes are composed either of rounded crystals deflated from the dry lake bed or of fine 'kopi', some of which may be due to weathering of saltated particles since deposition (Stephens & Crocker 1946; Campbell 1968; Bowler 1968, 1983; Chen *et al.* 1991).

In the Gawler Ranges area lunettes of gypseous composition occur on the eastern margin of lakes Everard, Harris, Acraman and of many of the smaller salinas. Both gypseous and siliceous lunettes are found on the eastern side of Lake Gairdner. The most prominent siliceous lunettes are located opposite the dunefields which impinge on the W side of the lake. Both dunefields found E of Lake Gairdner, the Piccadilly and the Beacon, are developed in the lee of these prominent siliceous lunettes. The lunette on the NE margin of Lake Gairdner rises about 35 m above the lake bed. Much of the surface is bare and erosion by wind and water has created a series of domical remnants, standing 3-4 m above gentle swales. In addition, lunettes consisting predominantly of fragments of Gawler Range Volcanics of sand size occur discontinously along the margin of Lake Gairdner (Fig. 1c).

Sedimentology

A total of 16 sand samples, each from the crest of a dune, and including at least one from each of the dunefields in the Gawler Ranges province, was examined to determine composition and grain morphology (Table 1) and grain size and related parameters were determined using 0.5 phi standard sieves.

The sand samples are all various shades of yellow-red (2.5 to 10 YR Munsell Soil Colours). All samples consist of at least 90%, and most more than 98%, quartz grains. The minor constituents are quartz rock, feldspar, Gawler Range Volcanics fragments, ?iron oxide and organic matter. In most samples the grains are predominantly frosted, but some are polished. Samples from two dunes in the Scrubby Peak Dunefield show higher percentages of polished grains. Grains from all samples show ferruginous coatings of yellow,

Fig. 7. Transverse crestal dune, Scrubby Peak Dunefield, Gawler Ranges, South Australia. View to the south to the Corrobinnie Depression. The crestal dune is about 8 m high.

TABLE 1. *Composition and grain morphology of samples from dunefields in the Gawler Ranges, South Australia.*

Sample	Dune type	Colour[1]	Composition[2]	Surface texture[3]	Surface coating[4]	Roundness[5]	Sphericity
Beacon Dunefield							
1	linear	2.5YR 5/6	quartz 95% (1,2,3,4,5)	85% MF 15% P	Y, O, R, B.	SR-SA, few R	high, some elongate
Piccadilly Dunefield							
2	linear	5YR 4/6	quartz 99% (1,2,4,5)	98% MF few P	Y, O	SA-SR, few R	high, some elongate
3	parabolic	5YR 5/6	quartz 99% (4,5)	98% MF few P	Y, O	SA-SR, few R, WR	high, some elongate
4	linear	2.5YR 4/8	quartz 99% (4,5)	95% MF few LF few P	Y, O, R	SA-SR, few R	high, some elongate
5	linear	2.5YR 4/8	quartz 98% (1,5)	98% MF 2% P	Y, R, B	SA-SR few R	high, some elongate
Hiern Dunefield							
6	linear	5YR 5/6	quartz 99% (1,4,5)	98% F 2% P	Y, O	SA-SR, few WR	high, some elongate
7	irregular	5YR 5/6	quartz 99% (4,5)	95% F 5% P	Y, O	SA-SR, few R	high, some elongate
8	linear	7.5YR 6/6	quartz 99% (1,4,5)	95% MF 5%P	Y, O	SA-SR, few R, WR	high, some elongate
9	linear	5YR 5/8	quartz 90% (1,3,4,5)	90% F 10% P	Y, O	A-SR some R	moderate, some high
Moonaree Dunefield							
10	linear	7.5YR 5/6	quartz 98% (1,4,5)	90% LF 10% P	Y, O	SA-SR, some A, R	high, some elongate
11	irregular	7.5YR 5/6	quartz 99% (4,5)	95% F 5% P	Y, O	SA-R, few WR	high, some elongate
Scrubby Peak Dunefield							
12	linear	7.5YR 5/6	quartz 95% (1,4,5)	95% MF 5% P	Y, R, B	SA-SR, few R, WR	high, some elongate
13	linear	10YR 5/4	quartz 99% (1,4,5)	70% MP 30% SF	Y, O, B	SA-SR, some R	high-moderate, some elongate
14	linear	10YR 6/4	quartz 99% (1,4,5)	50% P 50% F	Y, O	SA-SR, few R	high-moderate, some elongate
15	linear	7.5YR 4/6	quartz 98% (1,4,5)	98% F 2% P	Y, O	SA-SR, few A, R	high-moderate, some elongate
Ilkina Dunefield							
16	linear	7.5YR 6/6	quartz 98% (1,3,4)	70% LF 30% P	Y, O, R	SA-SR, few R	moderate-high, some elongate

[1] Munsell Soil colours.
[2] Minor constituents in brackets: 1: quartz rock. 2: feldspar. 3: Gawler Range Volcanics. 4: ?iron oxide. 5: organic material.
[3] F: frosted. P: polished. M: moderately. L: lightly.
[4] Y: yellow. O: orange. R: red. B: brown.
[5] SA: subangular. SR: subrounded. A: angular. R: rounded. WR: well rounded

and less commonly orange, red and brown, material, The grains in all samples are predominantly subangular to subrounded, with small amounts of angular and well-rounded grains. High to moderate sphericity is characteristic, with most samples containing some elongate grains.

The dune samples are all fine to medium grained sands (mainly 0.125 to 0.5 mm diameter - Folk 1968). They are well-sorted to poorly sorted, with most samples moderately well-sorted.

Age of the dunes

The sand of the Gawler Ranges dunes is typically a yellow-red colour (Table 1), suggesting sufficient time for initial weathering of clay, release of iron, and development of a faint ferruginous patina. The sand is not the brilliant red of the deserts of central Australia, nor the dusky red (10R 3/4 Munsell Soil Colour) of the sand derived from the local Gawler Range Volcanics. Some authors would attribute the contrasting colour to different source materials (Wasson 1983; Nanson *et al.* 1992). Others, e.g. Wopfner & Twidale (1967) and Walker (1979) consider that the intensity of the red colour increases with time and hence is an indication of the age of the dune.

In an attempt to attain a more precise estimate of age, sand from the Scrubby Peak Dunefield was tested for thermoluminescence (TL). Samples were taken from a falling dune on an unnamed hill (National Topographic Map Series Minnipa 5932, 1:100 000, Grid Reference NE316018) 1.5 km E of Scrubby Peak (Fig. 6b). The method was a variation on the "partial bleach" method developed for the TL dating of sediments by Wintle and Huntley (1982). The age is estimated by measuring the TL energy stored in the lattice of a suitable mineral, in this case, quartz. The time interval measured is the time since the stored energy was last reset to zero or near zero by exposure to solar ultra-violet radiation. After such a re-setting, energy accumulates again at a known rate by exposure to radiation in the environment from the naturally radioactive elements K, U, Th and from cosmic rays. The age is found from the so-called age equation:

$$\text{age} = \frac{\text{natural TL}}{\text{TL per unit dose} \times \text{dose rate.}}$$

Samples were recovered from depths of 35 and 70 cm within the dune by means of an auger, taking care to shield the sample from light during and after collection. After digestion with 20% HCl to remove carbonates and NaOH to remove clay, the 90-125 μm fraction was recoverd by sieving. A 40 minute etch with 40% HF removed feldspars and a surface layer of the quartz. Flotation on aqueous sodium polytungstate at a relative density of 2.67 followed; the end product was very pure quartz and it is on this sample that the measurements were carried out.

One of the problems with TL dating of sediments is uncertainty about the degree to which the TL was reset at the beginning of the time of interest. It is rare for the TL to be removed completely, even by prolonged exposure to sunlight. Moreover, the amount of relic TL varies from sample to sample and may vary with the age of the sample (Berger 1990). In the present investigation, it was found that the accumulated TL was small so that any uncertainty in the degree of resetting would result in significant uncertainty in the age. The level of resetting was found from a surface sample collected by pressing packing tape against the exposed dune surface. This showed that the TL clock had not been completely reset to zero in spite of the long time likely to have been spent in the sun by the sample in reaching its present position. Under these circumstances special procedures are necessary, as described by Prescott and Mojarrabi (1993). They make use of the fact that many quartz samples have a so-called "rapidly bleaching" peak (RBP) at 325°C in the thermoluminescence glow curves, which bleaches to near zero within a matter of minutes when exposed to light of wavelength longer than about 500 nm (Spooner *et al.* 1988). This means that exposures of the order of minutes to natural sunlight in the environment will have ensured that the trap concerned had been emptied completely and that, at least so far as the 325°C peak is concerned, the TL clock of the sediment was completely reset at the time of deposition. In addition, this peak emits in a wavelength band centred near 420 nm, so that an optical filter transmitting this band will be selective for the peak in question (Prescott & Fox 1990; Scholefield *et al.* 1994). The 325°C peak rides on an unbleached background, which is measured and allowed for by the procedures. The surface sample mentioned above had zero TL when measured with the revised procedures.

The TL is expressed in terms of an equivalent dose measured in grays (Gy). The equivalent doses are: for the 35 cm sample 1.24 ± 0.20 Gy; and for the 70 cm sample 1.53 ± 0.25 Gy. The dose rate has been measured by three essentially independent methods (Hutton & Prescott 1992). They are, with the relevant dose rates in brackets: *in situ* gamma ray spectrometry (0.153 ± 0.028 Gy ka^{-1}); thick source alpha counting for U and Th with X-ray spectrometry (XRS) for K (0.142 ± 0.029 Gy ka^{-1}); and delayed neutron analysis (DNA) for U, neutron activation analysis (NAA) for Th with XRS for K (0.168 ± 0.041 Gy ka^{-1}). The weighted average is 0.152 ± 0.010 Gy ka^{-1} for both the 35 cm and 70 cm samples.

Contributions for cosmic rays must be included. These are 0.21 ± 0.02 and 0.18 ± 0.02 Gy ka^{-1} for the 35 and 70 cm samples respectively (Prescott & Hutton 1988, 1994). It is worth noting that cosmic rays dominate the dose rate because the levels of K, U and Th are so extremely low (K - 0.04 ± 0.01%; U - 0.22 ± 0.06 ppm; Th - 1.0 ± 0.4 ppm). Over the time in question, changes in cosmic ray intensities are negligible (Prescott & Hutton 1994).

The dose rates are 0.35 ± 0.03 Gy ka^{-1} at 35 cm and 0.33 ± 0.03 Gy ka^{-1} at 70 cm. A contribution from systematic errors has been added. Hence, the age of the 35 cm sample is 3.7 ± 0.7 ka and of the 70 cm sample 4.6 ± 0.9 ka. Although the deeper sample has the greater TL age, the two ages are not statistically different and probably all that can be concluded is that the dune has been in place for about 4 ka.

This age is based on a single series of dates from one dune. Obviously, more age determinations are required. Nevertheless, the pale colour of the sand, to which previous reference has been made, and the lack of any carbonate accumulations in the dunes (despite its availability) are suggestive of a youthful age.

The general appearances are consistent with the TL dating in suggesting that the Gawler Ranges dunes are younger than the putative Late Pleistocene relic forms of NW Eyre Peninsula (Twidale *et al.* 1976) and are comparable to the Holocene forms of that area (Rankin & Flint 1991) and of the Simpson Desert (Wopfner & Twidale 1988, 1990). Nevertheless, the age determination obtained is for the uppermost layers of a dune and there is no evidence of the age of the sand at the base of the dune.

Origin of the dune sand

As mentioned previously, the provenance of the sand in dunefields, whether it is of local derivation or far-travelled, is controversial. The question can be clarified by a consideration of the sedimentologic characteristics of the dune and other sands. In the Gawler Ranges province, a local origin of the dune sands is precluded by their composition and granulometry as set out in Table 1. For example, the Scrubby Peak Dunefield overlies outcrops of Eucarro Dacite, and Yardea Dacite, with small areas of Yannabie Rhyodacite, Paney Rhyolite and, at the base of the Yardea Dacite, "black" dacite (Blissett *et al.* 1988, Fig. 8). The microscopic groundmass of the volcanic rocks is rich in quartz, but the grains are much smaller than those of the dune sands. There are no quartz phenocrysts in the dacite (Blissett 1986). No quartz of a size equal to, or greater than, that of which the Scrubby Peak dunes are composed (and hence susceptible to attrition to produce sand-sized grains) could be derived from the Yardea and Eucarro dacites which are the country rocks over which, overwhelmingly, the dunefields have extended. No lakes or streams which might constitute a possible source of sand in the dunes are known from within the province.

If it is accepted that the dunes of the Scrubby Peak and other dunefields of the western Gawler Ranges extended from the W or NW, then there are three other possible sources of the quartz sand.

First, there are outcrops in the western Gawler Ranges of Yannabie Rhyodacite and of Paney Rhyolite (Fig. 8), both of which contain phenocrysts of quartz of a size equal to, or greater than, the dune sand (0.2 to 2.0 mm in diameter - Blissett 1986). Similarly, and second, granite with abundant coarse quartz crystals crops out to the west of the Ranges (Blissett *et al.* 1988). But difficulties attach to these outcrops as sources of the dune sand: they are of limited extent (about 60 km^2 compared with the 300 km^2 of the Scrubby Peak Dunefield); and it can be questioned whether they could produce a volume of quartz sand compatible with that represented by the total of the dunes. Also the outcrops do not extend across the width of the dunefield, so that the spread of sand from them calls for varied strong winds, and for distribution in topographically difficult terrain. Moreover, the dunefield extends westwards, i.e. windwards, of the outcrops in question (Fig. 8). Against these arguments, the Gawler Range Volcanics form a regional basin structure so that before erosion to their present occurrences, the quartz-bearing members could have extended further to the W. In addition, the former shape and size of these members could have been very different from their present representatives. But, on the evidence, the rhyodacite, rhyolite and granite outcrops of the western ranges and adjacent areas do not seem likely sources of suitable quartz sand.

The third possibility is that the dune sand has been derived from the Corrobinnie Depression. This runs in a NW-SE direction west, and therefore windward, of the dunefield and contains detritus derived from the granite areas to the S, W and N as well as from the Gawler Ranges. It contains quartz comparable in size and character to the dune sand of the Scrubby Peak Dunefield (fine-grained, moderately well sorted, typically subrounded, frosted and coated with iron oxide - Gostin pers. comm. 1993). It is concluded that the dune sands of the Scrubby Peak Dunefield cannot have been derived from the disintegration of the Gawler Range Volcanics, but rather have been transported on the wind from the Corrobinnie Depression, a distance of at least 30 km. Even if derived from the rhyolite, rhyodacite and granitic outcrops, the sand must have travelled 25 km to cross the zone of dacitic bedrock. Given the wind regime, the northern arm of the Scrubby Peak Dunefield (X in Fig. 8) could only have

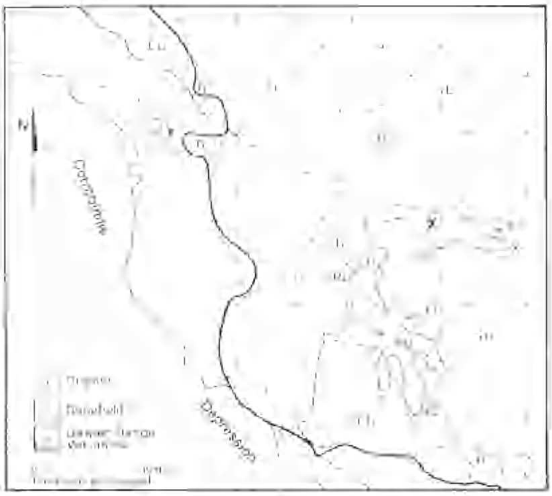

Fig. 8. Scrubby Peak Dunefield, western Gawler Ranges, South Australia, illustrating bedrock type and possible sources of the dune sand. X, Northern arm of the Dunefield. Y, Nearest upwind outcrop of rhyolite/rhyodacite. ED, Eucarro Dacite. YD, Yardea Dacite. R, Rhyolite. RD, Rhyodacite. See text for explanation. After Blissett *et al.* 1988.

originated in the rhyolitic/granitic outcrops indicated by Y in Fig. 8, or from outcrops further westward. Whether this would be considered far-travelled is a matter of definition, but the sand is certainly not of local derivation.

Mechanism of dune formation

Prevailing winds

It is suggested (see below) that the dunefields of the Gawler Ranges have been shaped by winds from the western sector. This is consistent with the putative source of the sand of which the dunes are constructed (see below). The relic linear dunes to the south of the Gawler Ranges, which possibly formed in late Pleistocene times, extended from NW to SE across the northern base of Eyre Peninsula, for they extend on to the western shores of salinas such as Lake Agars, but not on to the eastern shores (Twidale & Campbell 1985). These NW-SE dunes also extend well below low tide level between Cowell and Whyalla (Van Deur 1983[6]) but only in minor degree on the eastern side of the Gulf on northwestern Yorke Peninsula, where the aeolian forms were deposited during a phase of rising sea level and where the dunes are truncated by wave action at the coast (Jessup 1967, 1968). This is consistent with a wind regime dominated by northwesterlies.

In addition, at Lake Gairdner, the lunettes of the eastern shore are much more substantial than those of the western and, as the lunettes are comparable to coastal foredunes (Campbell 1968), this supports a westerly wind regime. Also, the huge Late Pleistocene calcareous aeolianite foredunes of west-facing shores in South Australia (e.g. on Eyre Peninsula) dwarf their east coast counterparts. Thus, there is evidence of a predominantly westerly wind regime in the Gawler Ranges and surrounding areas during the period, or periods, of dune formation.

There is, however, an anomaly between the present wind regime, as illustrated by the wind rose for Nonning (Fig. 2b) and the presumed westerly wind of dune formation, since the winter sand-moving winds blow from the westerly sector, whereas the summer sand-moving winds are from the SW, S and SE. It is presumed that most of the sand movement would take place in summer under hot and dry conditions, with only minor transport in the moist, cool and vegetated winter conditions. But, if there were only a slight latitudinal migration of climatic zones during the period of formation of the dunes, as suggested for example by Mabbutt (1977) and Sprigg (1979), then the region would have been influenced by summer rainfall maxima which would reduce sand movement during that season. On the other hand, dry winter conditions would be suitable for the evidenced transport of sand by westerly winds. The lack of compatibility between dune orientation and wind direction remains a problem.

But assuming a westerly wind regime, what factors are important in the formation of linear dunes? Why do parabolic dunes develop? How do the climbing and falling dunes form, and why do some of these forms continue across the crests of the hills, whereas others terminate on the upwind side only to resume on the lee slope? How are the transverse dunes formed?

Linear dunes

The origin of linear dunes is still debated (Cooke *et al.* 1993). Where the dunes have been closely examined, as in the Simpson Desert, these sand ridges appear to display the same range of morphology, and internal structures and temporal variations in asymmetry, indicative of formation under a bidirectional wind regime (McKee & Tibbetts 1964; Wopfner & Twidale 1967; Brookfield 1970; Tseo 1990, 1993). The linear dunes of the Gawler Ranges, however, developed in an upland setting rather than on desert plains. The confined valleys ought, in theory, to funnel the wind and hence to be conducive to a unidirectional wind regime, but bidirectional winds could be either dominant or be superimposed on unidirectional effects. No structures have been observed within the dunes and, though this may reflect absence of deep exposures as much as any diagnostic factor, it is not possible to state whether the dunes have been shaped under a unidirectional or a bidirectional wind regime.

Judging from the orientation of the linear dunes in the Gawler Ranges, the airflow was apparently disturbed by the hills of the province and was funnelled along valleys. The hills induce zones of increased and of decreased air flow and of enhanced turbulence. The dunes that are diverted around flanks of hills also reflect topographic control of the wind. The changes in dune orientation and morphology between, on the one hand, the Great Victoria Desert, and, on the other, the Gawler Ranges, are due to several factors. First, the westerly winds are diverted along the valleys. The linear dunes are not everywhere parallel with the regional air flow, as is characteristic of dunefields on plains but their orientation is, in part, determined by the local wind regime. Second, sand supply decreases within the upland where the silicic volcanic rocks weather less readily than do the granites to the west and, in particular, the supply of quartz grains is reduced. Third, sand movement is impeded as a result of the presence of near surface moisture, held either in valley alluvium or in rock fractures, and consequent vegetation growth.

---

[6] VAN DEUR, W. J. (1983) Submerged dunes of northeastern Eyre Peninsula. MA thesis, University of Adelaide (Unpub.)

Because of the lack of observed structures in the dunes, the uncertainty about the relationship between dune morphology and wind regime and the fact that the dunes are relic and possibly related to different wind velocities, wind directions and rainfall amounts and distributions, the classification of the dunes as linear, i.e. elongate forms aligned in the direction of the dominant sand moving winds, is tentative.

Parabolic dunes

The occurrence of parabolic rather than linear dunes, can be explained as follows. In the Corrobinnie Depression to the S of the Gawler Ranges (Bourne *et al.* 1974) and elsewhere (McKee 1966; Wasson *et al.* 1983) parabolic dunes are located in low lying areas characterised by an abundant supply of sand and by proximity to groundwaters, which leads to the lower parts of the dune being stabilised by moisture and vegetation. This allows the higher zones of sand to be transported downwind to give blowouts or U dunes. In the Gawler Ranges area the parabolic dunes occur only in wide open valleys and on plains, for example in the western Moonaree Dunefield and in patches in the Piccadilly Dunefield. However, they are not necessarily restricted to the lowest parts of these valleys. On the available evidence and as indicated on the 1:100 000 topographic map with a contour interval of 20 m, the W-E belt of parabolic dunes in the Moonaree Dunefield is sharply delimited on the northern side by a belt of linear dunes and, less sharply, on the southern side by dune-free plains. The parabolic dunes override low N-S rises in the valley and linear dunes occupy some low-lying areas in the northern part of the dunefield. Thus, in addition to stabilisation by vegetation and an abundant supply of sand, parabolic dune formation may require a critical wind velocity such as is attained only in wide valleys and on plains.

Climbing and falling dunes

The climbing and falling dunes are a particular variety of linear dune which rise and descend topographic obstructions where the local wind is strong enough to carry the available sand grains up and over the topographic rises. The wind velocity is apparently reduced on approaching the obstacle and deposition of sand occurs. Many of the bounding slopes of the bornhardts are gentle (about 5-12°) and reverse eddy flow is generally not developed, and hence echo dunes (Tsoar 1983; see also Fig. 6a) are not found windward of cliffed obstacles. Where the supply is sufficient, sand accumulates until the dune reaches the height of the obstruction. Where the bornhardt is low (in the Gawler Ranges <40 m) the dune extends on to and over the crest as a climbing and falling dune. Where the bornhardt is high (>40 m), the dune form may be discontinous though sand is carried on to the crest, as evidenced by grains trapped in basins and crevices. Downwind of the obstacle, however, there is a zone of reduced wind velocity and sand deposition and dune formation occur. There may be further funnelling of the sand to the lee of the obstacle where the falling dune is resumed in a topographic embayment (Fig. 6d). The contrast between those linear forms that continue unbroken over crests of bedrock hills and those in which the climbing and falling components are separated, evidently reflects the Bernouilli effect (Pye & Tsoar 1990).

Transverse dunes

The transverse dunes of the Scrubby Peak Dunefield occur immediately downwind of the Corrobinnie Depression, the presumed source of the sand, and where the sand supply is abundant. The bornhardts in this area stand about 100 m above the level of the plain, form N-S trending ridges and the bounding slopes are generally 5-10° with some as steep as 18°. The plain is sand covered, with linear dunes of varied orientation, but generally NW-SE where there are no topographic obstacles, N-S in the valleys and W-E on the bornhardts rises (Fig. 4). Some of the N-S linear dunes override topographic obstacles and hence are classed as climbing and falling dunes. The W-E transport of sand across the bornhardt rises also explains the presence of sand in the valleys. However, some of the dunes are limited to the upper slopes of the bornhardts and are located immediately to the lee of the crest of the bornhardts (Fig. 7). Although they may be linear dunes formed by winds from a northerly or southerly direction, in which case they do not conform to the pattern of dunes throughout the region, it is more likely that these crestal dunes are transverse to the originating wind. It is suggested than the sand in these transverse dunes was driven up the windward slope of the bornhardts and little or no deposition occurred here due to acceleration of the air flow. However, immediately downwind of the crest, separation of the air flow and deceleration occurred so that deposition of sand eventuated. However, further downwind, air flow accelerated and no dune formed.

It is suggested that in this area the dunes are a result of two different wind regimes: one a NW-SE wind that was deflected by the topography and one a NW-SE wind that was of sufficient strength to transport sand over the obstacles.

Significance of lunettes and salinas in sand supply

The lunettes located on the eastern shore of Lake Gairdner evidently spawn fields of linear dunes in their lee in a manner similar to that described from the Simpson and other deserts (Twidale 1972, 1981). The transport of sand to the salinas by rivers and the formation of the lunettes are important influences on sand supply and dune formation. Whether sand is carried by the wind from the W to the E shore of Lake

Gairdner (some 30 km) has not been determined. No dunes have been observed on the bed of the lake (J. Andrews, pers. comm. 1994), though small barchanoid forms have been reported on the bed of Lake Harris (R. Major, pers. comm. 1992). Sand could be carried by saltation across the salina. Given the hygroscopic character of the halite crust this may be difficult to conceive, though Clarke (1994) described saltation on some salinas in Western Australia and S. Wells (pers. comm. 1994) has observed grains saltating across a salt surface in California. Alternatively, sand reaching the W shore on the wind could be carried by wave action to the E shore during the occasional periods when there is water in the lake (Campbell 1968), though not from the lake bed unless the salt crust is dissolved or otherwise removed. Small ephemeral salt dunes, noted on the eastern shore of Lake Gairdner, indicate the temporary redistribution of some of the salt by deflation.

Conclusion

More data on the dunes of the Gawler Ranges province are required before firm conclusions can be drawn concerning the origin and age of the various dune forms. The available information suggests that the variations in morphology depend, at least in part, on supply of sand, moisture content of the substrate, vegetation cover, wind speed and direction, and topographic interference to the wind. The suggestion that the formation of parabolic as opposed to linear dunes is dependent on an abundant supply of sand and fixing of the dune by vegetation only partially explains the distribution of these dune types in the Gawler Ranges province; other factors are apparently involved. Climbing dunes are a variant of linear dunes and form in the zone of reduced wind velocity upwind of an obstacle where the slope of the obstacle is gentle and does not generate reverse eddy flow. Falling dunes are associated with climbing dunes provided the sand supply is sufficient. They develop in the zone of reduced wind velocity to the lee of the obstacle. The crestal transverse dunes are also due to deposition in the zone of reduced wind velocity. Though the dunes of the Gawler Ranges area are essentially relic and are now stabilised by vegetation, there is sand movement during very high winds. The dunes were active about 4000 years BP. The dunes of the Scrubby Peak Dunefield in the southern Gawler Ranges demonstrate that here the sand has been transported by the wind at least 25 km from its source.

Acknowledgments

The authors thank J. A. Bourne for assistance in the field, V. A. Gostin for advice on sedimentology, K. Moxham for advice concerning air flow around obstacles and R. Rice, R. Barrett and S. Proferes for technical assistance. Two referees gave helpful suggestions on an earlier draft of the paper.

References

AHLBRANDT, T. S. (1979) Textural parameters of eolian deposits *In* McKee, E.D. (Ed.) "A Study of global sand seas". *U.S.G.S. Prof. Pap.* **1052**, 21-51.

BENDER, G. L. (1982) "Reference handbook on the deserts of North America" (Greenwood Press, Westport).

BERGER, G. W. (1990) The effectiveness of natural zeroing of the thermoluminescence in sediments. *J. Geophy. Res.* **95**, 12375-12397.

BIGARELLA, J. J. (1975) Lagoa dune field (State of Santa Catarina, Brazil), a model of eolian and pluvial activity. *Bol. Paranaense Geociências* **33**, 133-167.

______ (1979) The Lagoa dune field, Brazil *In* McKee, E. D. (Ed.) "A study of global sand seas". *U.S.G.S. Prof Pap.* **1052**, 114-134.

BINKS, P. J. & HOOPER, G. J. (1984) Uranium in Tertiary palaeochannels, "West Coast" area, South Australia. *Austsn. Inst. Min. Metall. Proc.* **289**, 271-285.

BLISSETT, A. H. (1986) Subdivisions of the Gawler Range Volcanics in the Gawler Ranges. *Geol. Surv. S. Aust. Quart. Geol. Notes* **97**, 2-11.

______, PARKER, A. J. & CROOKS, A. F. (1988) YARDEA map sheet, Geological Atlas of South Australia. 1:250 000 series (Geol. Surv. S. Aust., Adelaide).

______, ______ & SCHEFFLER, J. (1989) Gawler Ranges Excursion October 6-9th, 1989. *S.A. Dept. Mines & Energy Rept Bk* **89/70**.

BOURNE, J. A., TWIDALE, C. R. & SMITH, D. M. (1974) The Corrobinnie Depression, Eyre Peninsula, South Australia. *Trans. R. Soc. S. Aust.* **98**, 139-152.

BOWLER, J. M. (1968) Australian landform example: lunette. *Aust. Geogr.* **10**, 402-404.

______ (1983) Lunettes as indices of hydrologic change; a review of Australian evidence. *Proc. R. Soc. Vict.* **95**, 147-168.

BROOKFIELD, M. (1970) Dune trends and wind regime in central Australia. *Z. Geomorph. Suppl.* **10**, 121-153.

BUREAU OF METEOROLOGY (1988) "Climatic Atlas of Australia. Map Set 8." (Australian Government Publication Service, Canberra).

______ (1993a) "Rainfall statistics Region 16" (microfiche) (National Climate Centre, Bureau of Meteorology, Melbourne).

______ (1993b) "Surface wind analysis" (National Climate Centre, Bureau of Meteorology, Melbourne).

CAMPBELL, E. M. (1968) Lunettes in southern South Australia. *Trans. R. Soc. S. Aust.* **92**, 85-109.

______ & TWIDALE, C. R. (1991) The evolution of bornhardts in silicic volcanic rocks in the Gawler Ranges. *Aust. J. Earth Sci.* **38**, 79-93.

CHEN, X. Y., BOWLER, J. M. & MAGEE, J. W. (1991) Aeolian landscapes in central Australia: gypsiferous and quartz dunes environments from Lake Amadeus. *Sediment.* **38**, 519-538.

CLARKE, J. D. A. (1994) Evolution of the Lefroy and Cowan palaeodrainage channels. *Aust. J. Earth Sci.* **41**, 55-69.

COOKE, R., WARREN, A. & GOUDIE, A. (1993) "Desert Geomorphology" (University College London Press, London).

Cros, L. & Serra, J. (1993) A complex dune system in Baix Emporda (Catalonia, Spain) *In* Pye, K. (Ed.) "The Dynamics and Environmental Context of Aeolian Sedimentary Systems". *Geol. Soc. Spec. Publ.* **72**, 191-199.

Evans, J. R. (1962) Falling and climbing sand dunes in Cronese ("Cat") Mountains, San Bernardino County, California. *J. Geol.* **70**, 107-113.

Eyre, E. J. (1845) "Journals of expeditions into Central Australia. Vol. 1." (Borne, London).

Fanning, C. M., Blissett A. H., Flint, A. B., Ludwig, K. R. & Parker, A. J. (1986) A refined geological history of the Gawler Craton through U-Pb zircon dating of acid volcanics. *Geol. Soc. Aust. Abst.* **15**, 67-68.

Flint, R. B. (1993) Hiltaba Suite. *In* "The Geology of South Australia. Vol. 1. The Precambrian" *S.A. Geol. Surv. Bull.* **54**, 127-131.

Folk, R. L. (1968) "Petrology of sedimentary rocks" (Hemphill's, Austin).

______ (1971) Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia, 1: geomorphology and grain size relationships. *Sediment.* **16**, 5-54.

Goudie, A. (1972) Climate, weathering, crust formation, dunes and fluvial features of the central Namib Desert, near Gobabeb, South West Africa. *Madoqua* (series 2) **2**, 15-31.

Greeley, R. (1985) "Planetary Landscapes" (George Allen & Unwin, London).

______ & Iverson, J. D. (1985) "Wind as a geological process on Earth, Mars, Venus and Titan" (Cambridge University Press, Cambridge).

Hills, E. S. (1940) The lunette, a new landform of aeolian origin. *Aust. Geogr.* **3**, 15-21.

Hutton, J. T. & Prescott, J. R. (1992) Field and laboratory measurements of low-level thorium, uranium and potassium. *Nuclear Tracks Radiat. Meas.* **20**, 367-370.

Jennings, J. N. (1957) On the orientation of parabolic or U dunes. *Geogr. J.* **122** (4), 474-480.

Jessup, R. W. (1967) The late-Quaternary eustatic and geological history of northern Yorke Peninsula, South Australia *In* Morrison, R. B. & Wright, H. E. (Eds) "Means of Correlation of Quaternary Successions" *Proceedings VII Congress, International Association for Quaternary Research* **8**, 395-406.

______ (1968) Soil development in coastal South Australia in relation to glacio-eustatic changes of sealevel. *IXth International Congress of Soil Science Transactions* **IV**, 641-649.

Johnson, R. B. (1968) The Great Sand Dunes of southern Colorado. *Mountain Geol.* **5**, 23-29.

Lancaster, N. (1994) Controls on aeolian activity: some new perspectives from the Kelso Dunes, Mojave Desert, California. *J. Arid Environments* **27**, 113-125.

Langford-Smith, T. & Thom, B. (1969) New South Wales coastal morphology. *J. Geol. Soc. Aust.* **16**, 572-580.

Livingstone, I. & Thomas, D. S. G. (1993) Modes of linear dune activity and their palaeoenvironmental significance: an evaluation with reference to southern African examples *In* Pye, K. (Ed.) " The Dynamics and Environmental Context of Aeolian Sedimentary Systems." *Geol. Soc. Spec. Publ.* **72**, 91-101.

Mabbutt, J. A. (1977) "Desert landforms" (Australian National University Press, Canberra)

Madigan, C. T. (1936) The Australian sand-ridge deserts. *Geogrl. Rev.* **26**, 205-227.

______ (1946) The Simpson Desert Expedition, 1939, Scientific Report No. 6, Geology - the sand formations. *Trans. R. Soc. S. Aust.* **70**, 45-63.

Mainguet, M. (1984) A classification of dunes based on aeolian dynamics and the sand budget pp. 31-58 *In* El-Baz, F. (Ed.) "Deserts and arid lands" (Martinus Nijhoff, Denhaag)

McKee, E. D. (1966) Structures of dunes at White Sands National Monument, New Mexico, and comparison with structures of dunes from other selected areas. *Sediment.* **7**, 1-69.

______ (Ed.) (1979) A study of global sand seas. *U.S.G.S. Prof. Pap.* **1052**.

______ & Tibbetts, G. C. (1964) Primary structures of a seif dune and associated deposits in Libya. *J. Sedim. Petrol.* **34**, 5-17.

Nanson, G. C., Chen, X. Y. & Price, D. M. (1992) Lateral migration, thermoluminescence chronology and colour variation of longitudinal dunes near Birdsville in the Simpson Desert, Central Australia. *Earth Surface Proc. Landforms* **17**, 807-819.

Planhol, X. De & Rognon, P. (1970) "Les Zones Tropicales Arides et Subtropicales" (Armand Colin, Paris).

Prescott, J. R. & Fox, P. J. (1990) Dating quartz sediments using the 325°C TL peak: new spectral data. *Ancient TL* **8**, 32-35.

______ & Hutton, J. T. (1988) Cosmic ray and gamma ray dosimetry for TL and ESR. *Nuclear Tracks* **14**, 223-227.

______ & ______ (1994) Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiat. Meas.* **23**, 497-500.

______ & Mojarrabi, B. (1993) Selective Bleach - An improved "partial bleach" method of finding equivalent doses for thermoluminescence dating of quartz. *Ancient TL* **11**, 27-30.

Pye, K. & Tsoar, H. (1990) "Aeolian sand and sand dunes" (Unwin Hyman, London).

Rankin, L. R. & Flint, R. B. (1991) "Streaky Bay. 1:250 000 Geological Series - Explanatory Notes" (Geol. Surv. S. Aust., Adelaide).

Scholefield, R. B., Prescott, J. R., Franklin, A. D. & Fox, P. J. (1994) Observations on some thermoluminescence emission centres in geological quartz. *Radiat. Meas.* **23**, 409-412.

Seppälä, M. (1993) Climbing and falling dunes in Finnish Lapland *In* Pye, K. (Ed.) "Dynamics and Environmental Context of Aeolian Sedimentary Systems" *Geol. Soc. Spec. Publ.* **72**, 269-274.

Smith, H. T. U. (1954) Eolian sand on desert mountains. *Geol. Soc. Amer. Bull.* **65**, 1036-1037.

Smith, R. S. U. (1982) Sand dunes in the North American deserts pp. 481-524 *In* Bender, G. L. (Ed.) "Reference handbook on the deserts of North America" (Greenwood Press, Westport).

Spooner, N. A., Prescott, J. R. & Hutton, J. T. (1988) The effect of illumination wavelength on the bleaching of the thermoluminescence of quartz. *Quat. Sci. Rev.* **7**, 325-329.

Sprigg, R. C. (1979) Stranded and submerged sea-beach systems of southeastern South Australia and the aeolian desert cycle. *Sed. Geol.* **22**, 53-97.

Stephens, C. G. & Crocker, R. L. (1946) Composition and genesis of lunettes. *Trans. R. Soc. S. Aust.* **70**, 302-312.

Stone, R. O. (1967) A desert glossary. *Earth Sci. Rev.* **3**, 211-268.

Thom, B., Hesp, P. & Bryant, B. (1994) Last glacial "coastal" dunes in Eastern Australia and implications for landscape stability during the Last Glacial Maximum. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **111**, 229-248.

Tseo, G. (1990) Reconnaissance of the dynamic characteristics of an active Strzelecki longitudinal dune, south central Australia. *Z. Geomorph.* **34**, 19-36.

______ (1993) Two types of longitudinal dune fields and possible mechanisms for their development. *Earth Surface Proc. Landforms* **18**, 627-643.

Tsoar, H. (1983) Wind tunnel modelling of echo and climbing dunes *In* Brookfield, M. E. & Ahlbrandt, T. S.

(Eds) "Eolian Sediments and Processes" *Developments in Sedimentology* **38**, 247-259.

______ (1989) Linear dunes - forms and formation. *Prog. Phys. Geog.* **13**, 507-528.

TWIDALE, C. R. (1972) Evolution of sand dunes in the Simpson Desert, Central Australia. *Trans. Inst. Brit. Geogr.* **56**, 77-109.

______ (1981) Age and origin of longitudinal dunes in the Simpson and other sand ridge deserts. *Die Erde* **112**, 231-241.

______, BOURNE, J. A. & SMITH, D. M. (1976) Age and origin of palaeosurfaces on Eyre Peninsula and the southern Gawler Ranges, South Australia. *Z. Geomorph.* **20**, 28-55.

______ & CAMPBELL, E. M. (1985) The form of the land surface pp. 57-76 *In* Twidale, C. R., Tyler, M. J. & Davies, M. (Eds) "Natural History of Eyre Peninsula" (Royal Society of South Australia, Adelaide).

WALKER, T. R. (1979) Red color in dune sand pp. 52-81 *In* McKee, E. D. (Ed.) "A study of global sand seas" *U.S.G.S. Prof. Pap.* **1052**.

WASSON, R. (1983) Dune sediment types, sand colour, sediment provenance and hydrology in the Strzelecki-Simpson Dunefield, Australia *In* Brookfield, M. E. & Ahlbrandt, T. S. (Eds) "Eolian Sediments and Processes" *Developments in Sedimentology* **38**, 165-195

______, RAJAGURU, S. N., MISRA, V. N., AGRAWAL, D. P., DHIR, R. P., SINGHVI, A. K. & KAMESWARO RAO, K. (1983) Geomorphology, Late Quaternary stratigraphy and palaeoclimatology of the Thar dunefield. *Z. Geomorph. Suppl.-Bd.* **45**, 117-151.

______, FITCHETT, K., MACKEY, B. & AHLBRANDT, T. S. (1988) Large-scale patterns of dune type, spacing and orientation in the Australian continental dunefield. *Aust. Geogr.* **19**: 89-104.

WILLIAMS, G. E. (1994) Acraman, South Australia: Australia's largest meteorite impact structure. *Proc. R. Soc. Vict.* **106**, 105-127.

WILSON, I. G. (1973) Ergs. *Sed. Geol.* **10**, 77-106.

WINTLE, A. G. & HUNTLEY, D. J. (1982) Thermoluminescence dating of sediments. *Quat. Sci. Rev.* **1**, 31-53.

WOPFNER, H. & TWIDALE, C. R. (1967) Geomorphological history of the Lake Eyre Basin pp. 119-143 *In* Jennings, J. N. & Mabbutt, J. A. (Eds) "Landform studies from Australia and New Guinea" (Cambridge University Press, Cambridge).

______ & ______ (1988) Formation and age of desert dunes in the Lake Eyre depocentres in central Australia. *Geol. Rundschau* **77**, 815-834.

______ & ______ (1990) Dunefields pp. 45-60 *In* Tyler, M. J., Twidale, C. R., Davies, M. & Wells, C. B. (Eds) "Natural History of the North East Deserts" (Royal Society of South Australia, Adelaide).